

71st Annual DFD Meeting of The American Physical Society

19 November 2018

Direct numerical simulation of turbulent forced convection with roughness

Michael MacDonald*, Nicholas Hutchins & Daniel Chung



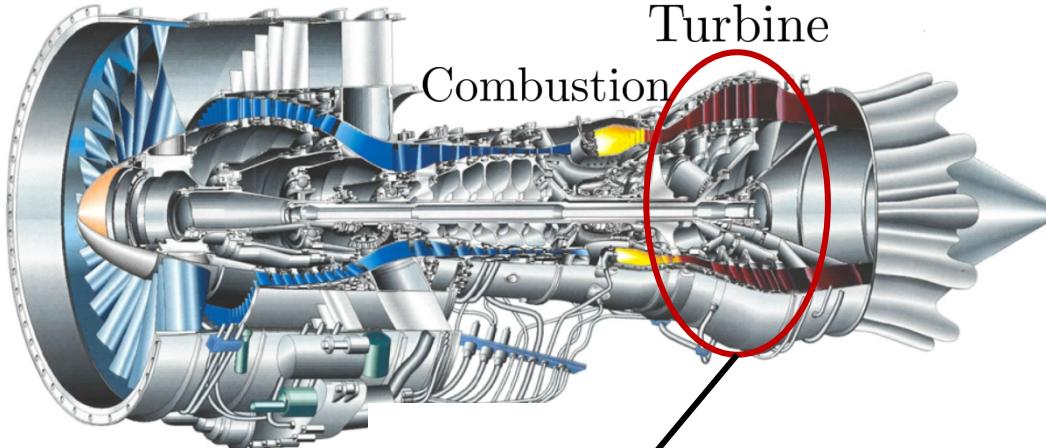
*Now at Jet Propulsion Laboratory, Caltech

Motivation

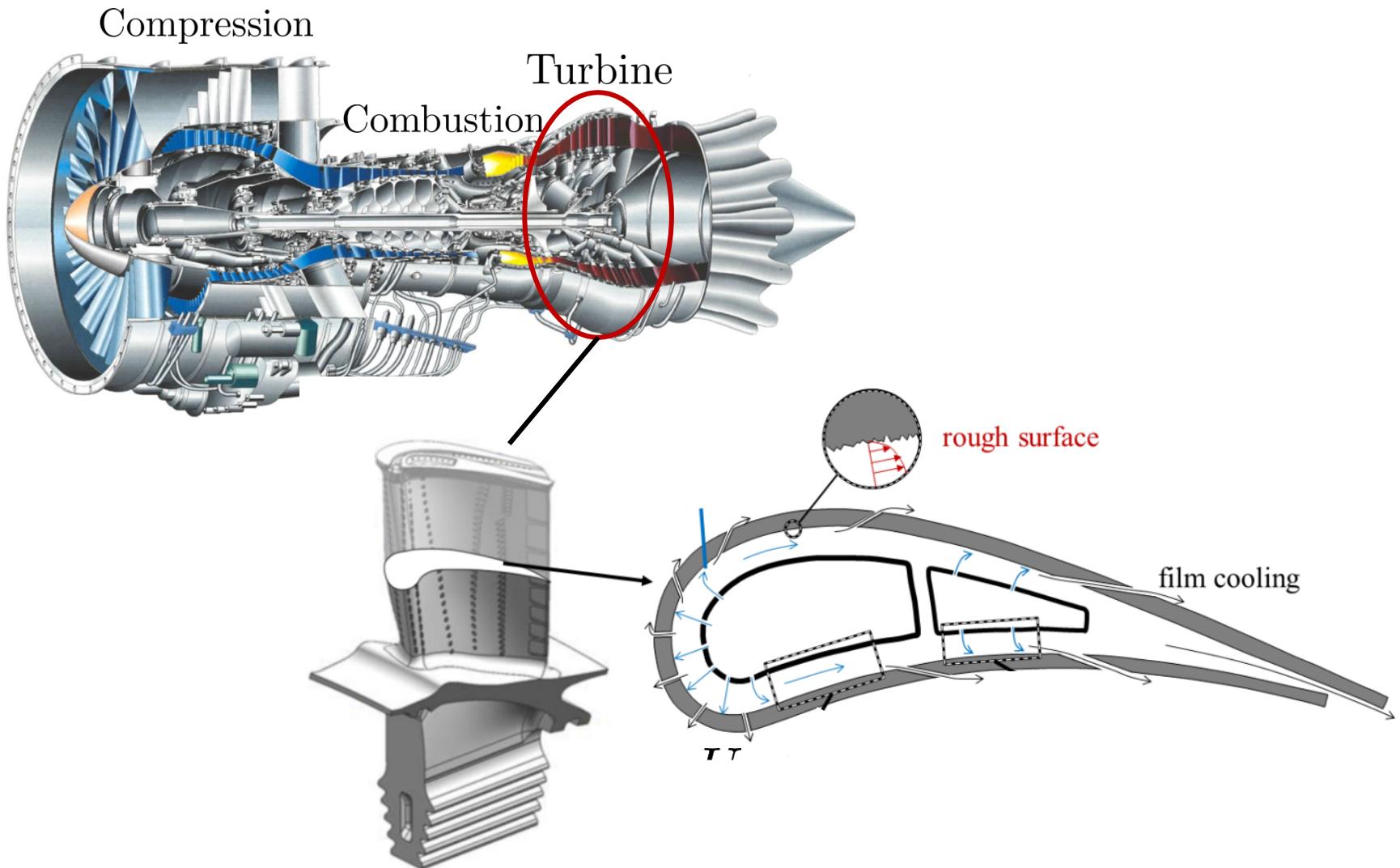
Compression

Turbine

Combustion

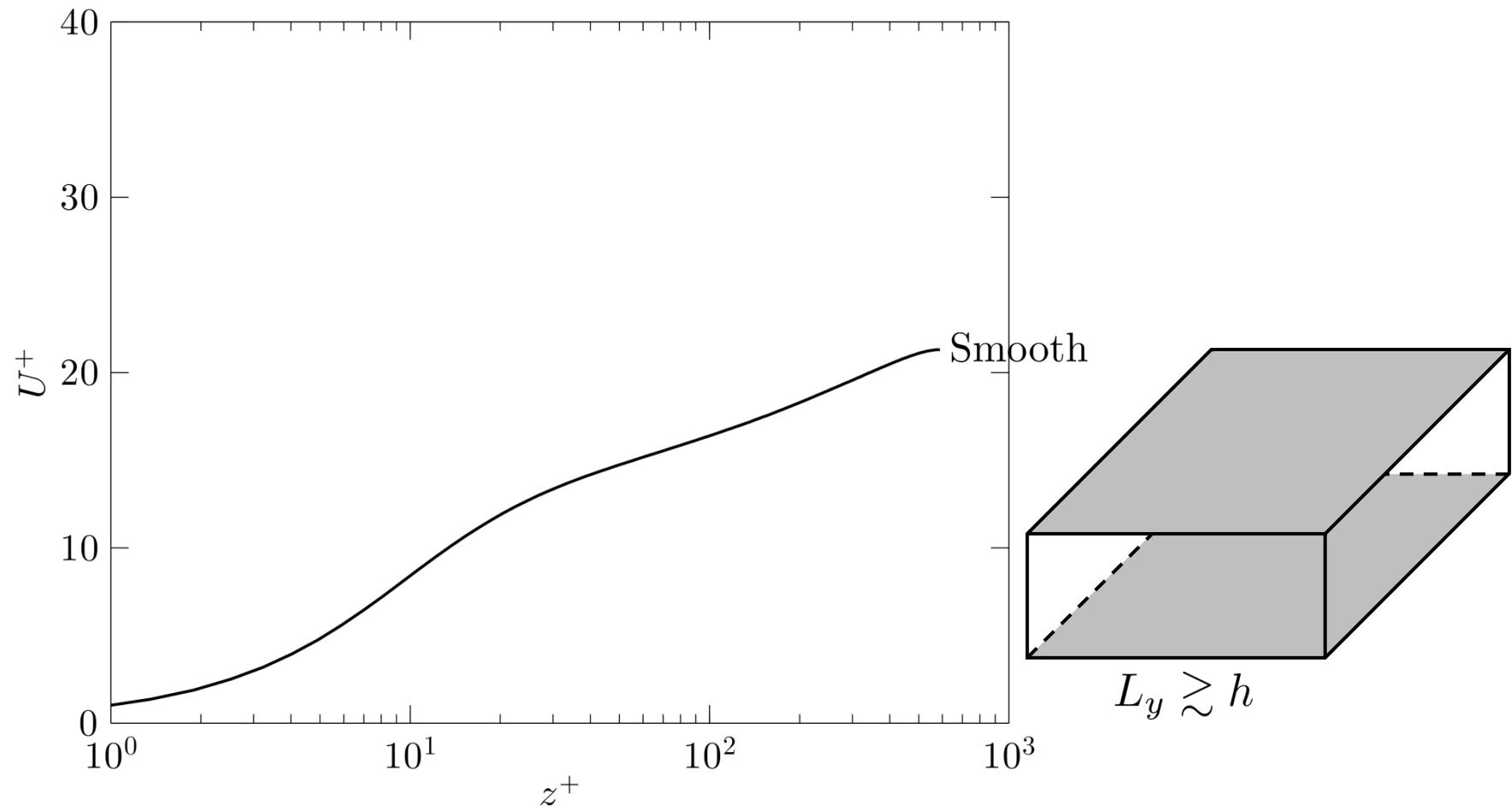


Motivation



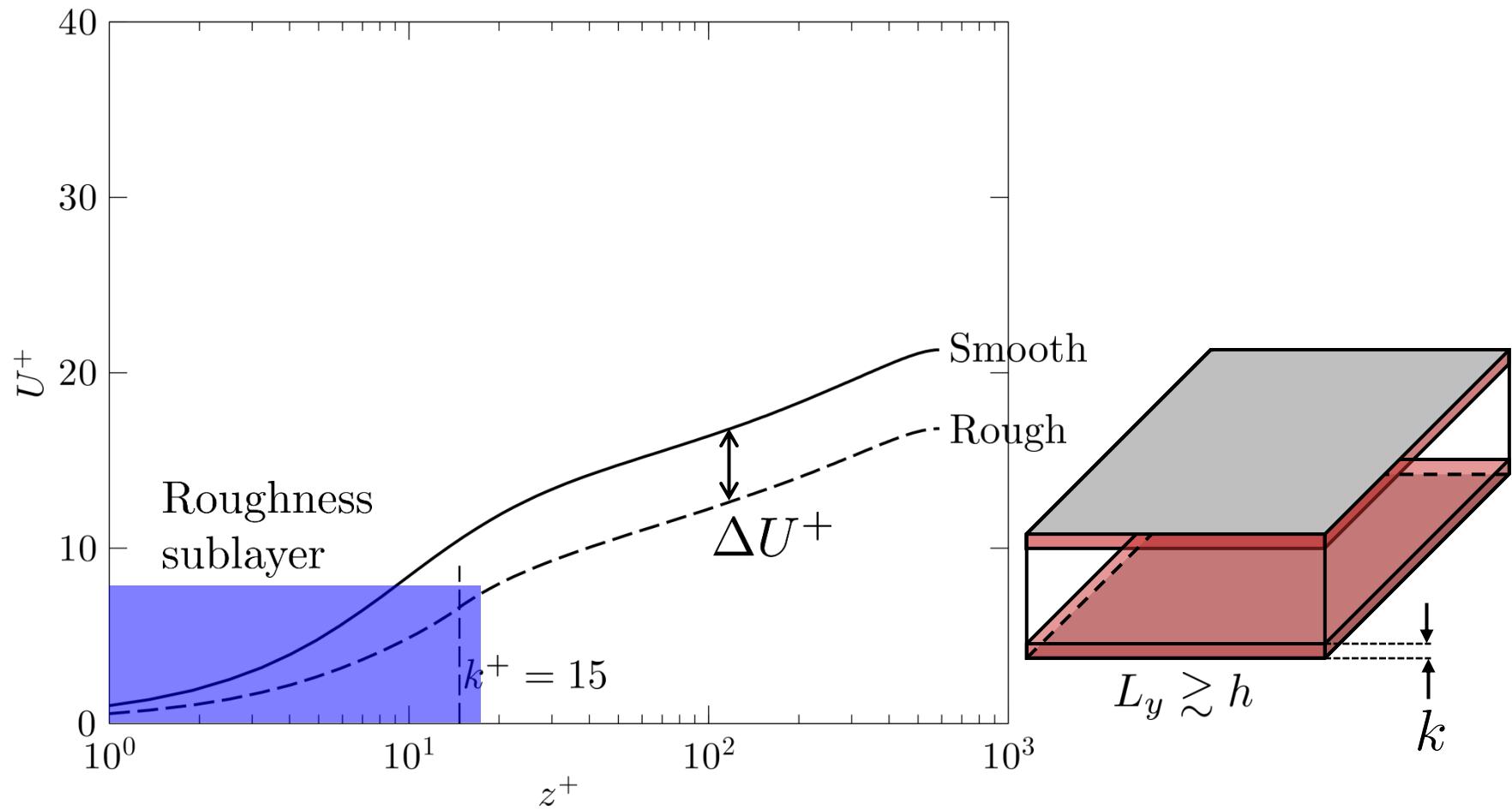
Minimal-Span Channel

Chung *et al.* (2015, JFM), MacDonald *et al.* (2017, JFM)



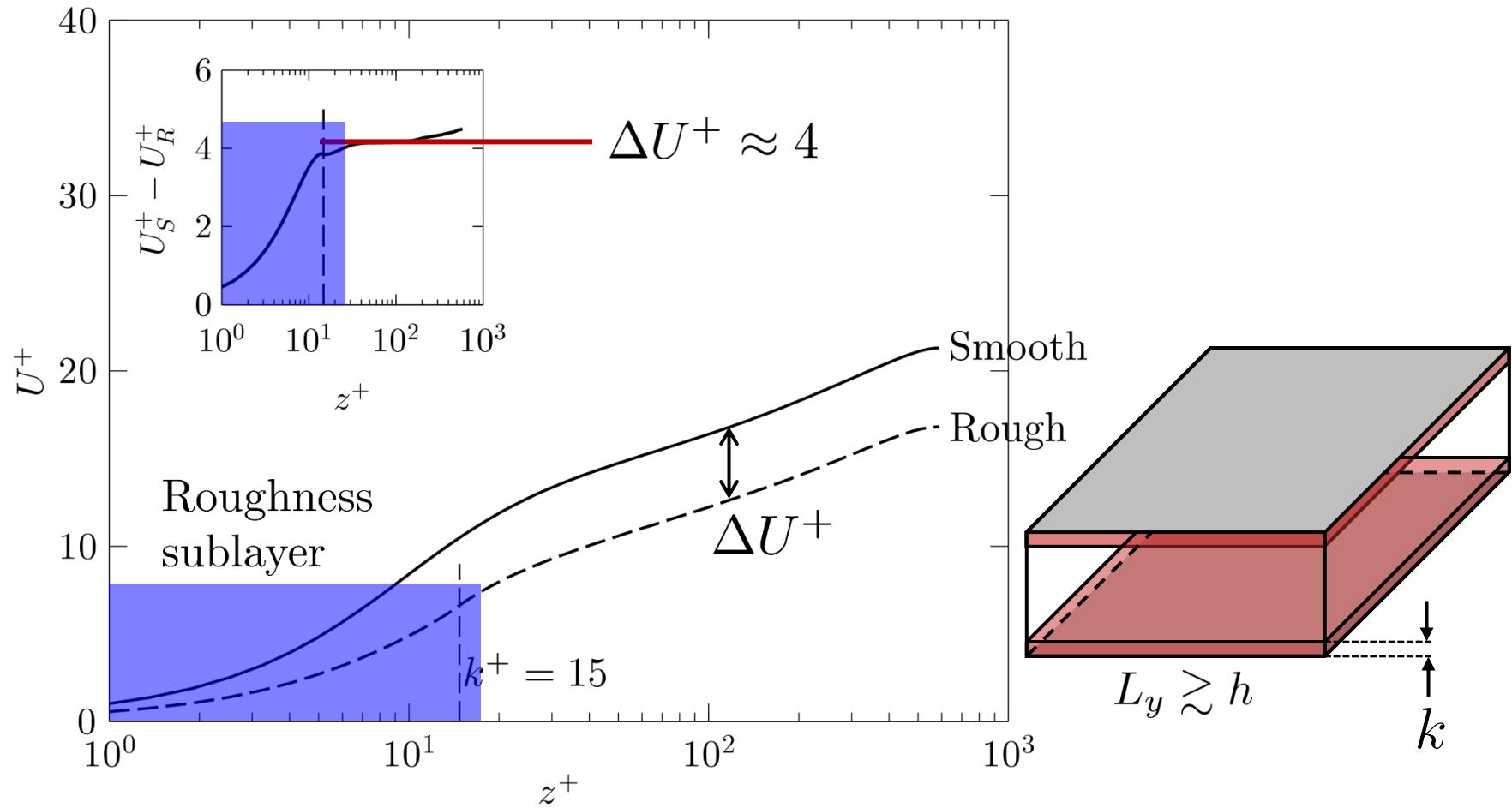
Minimal-Span Channel

Chung *et al.* (2015, JFM), MacDonald *et al.* (2017, JFM)



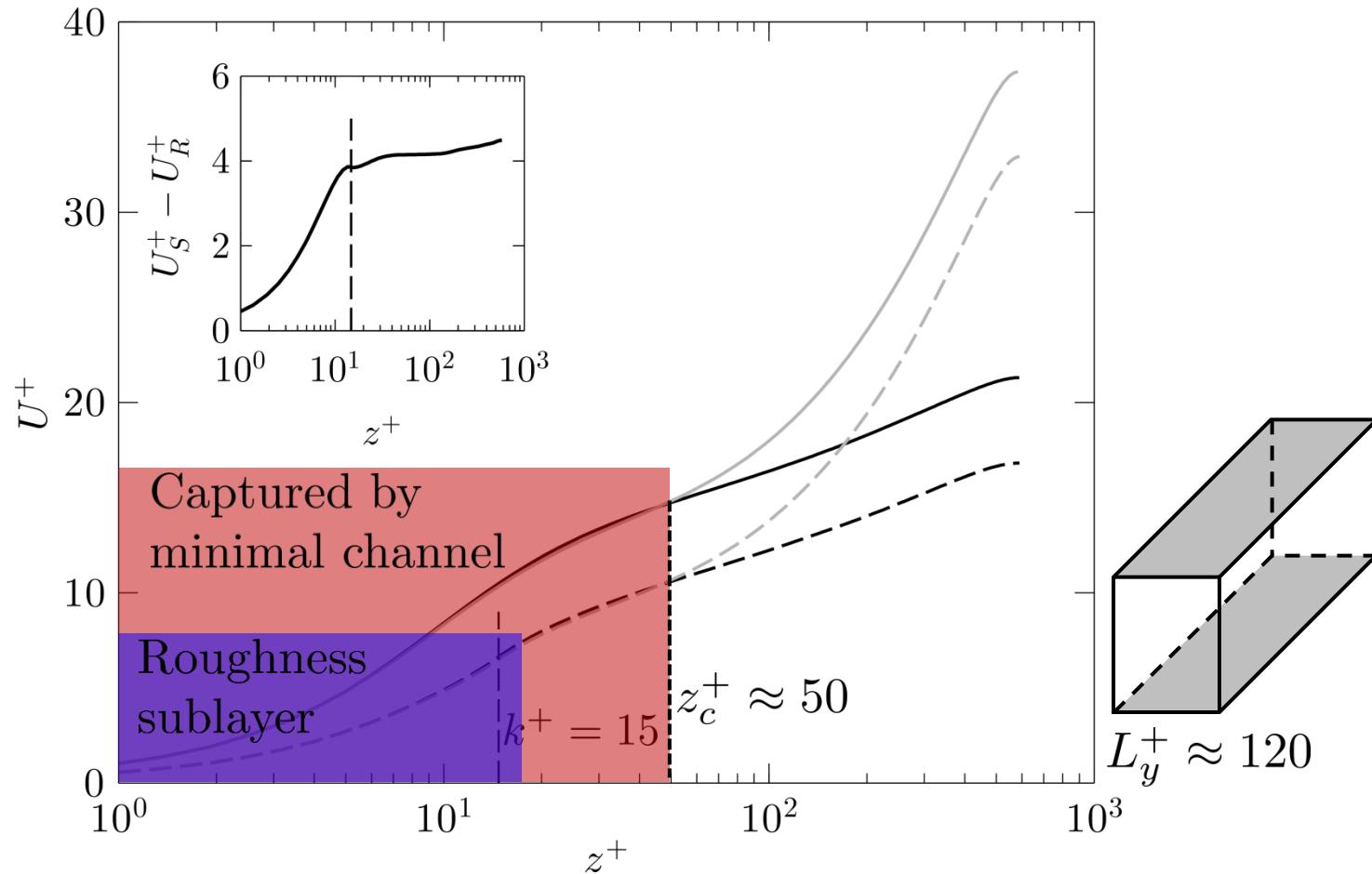
Minimal-Span Channel

Chung *et al.* (2015, JFM), MacDonald *et al.* (2017, JFM)



Minimal-Span Channel

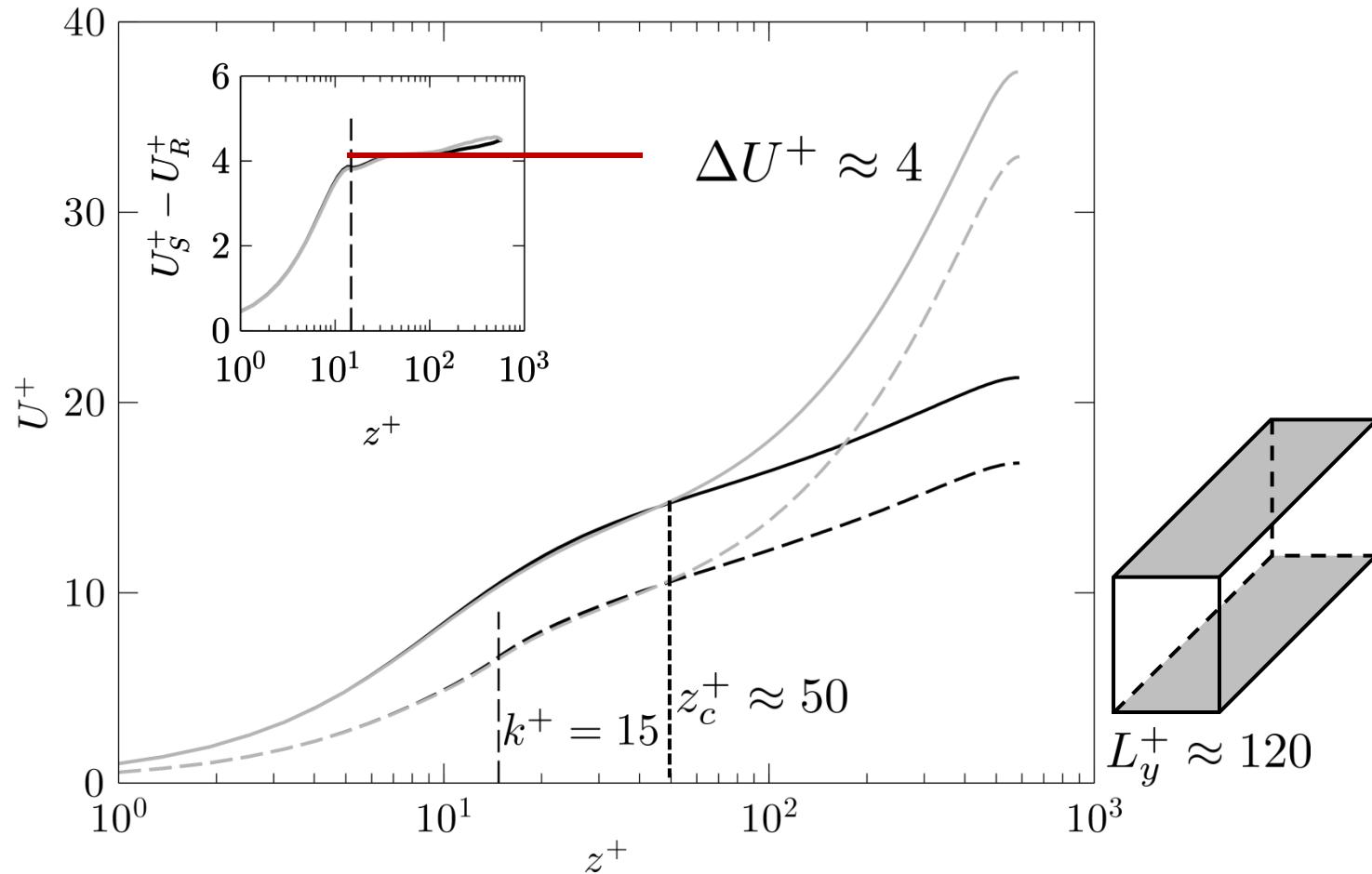
Chung *et al.* (2015, JFM), MacDonald *et al.* (2017, JFM)



$$z_c^+ \approx 0.4L_y^+$$

Minimal-Span Channel

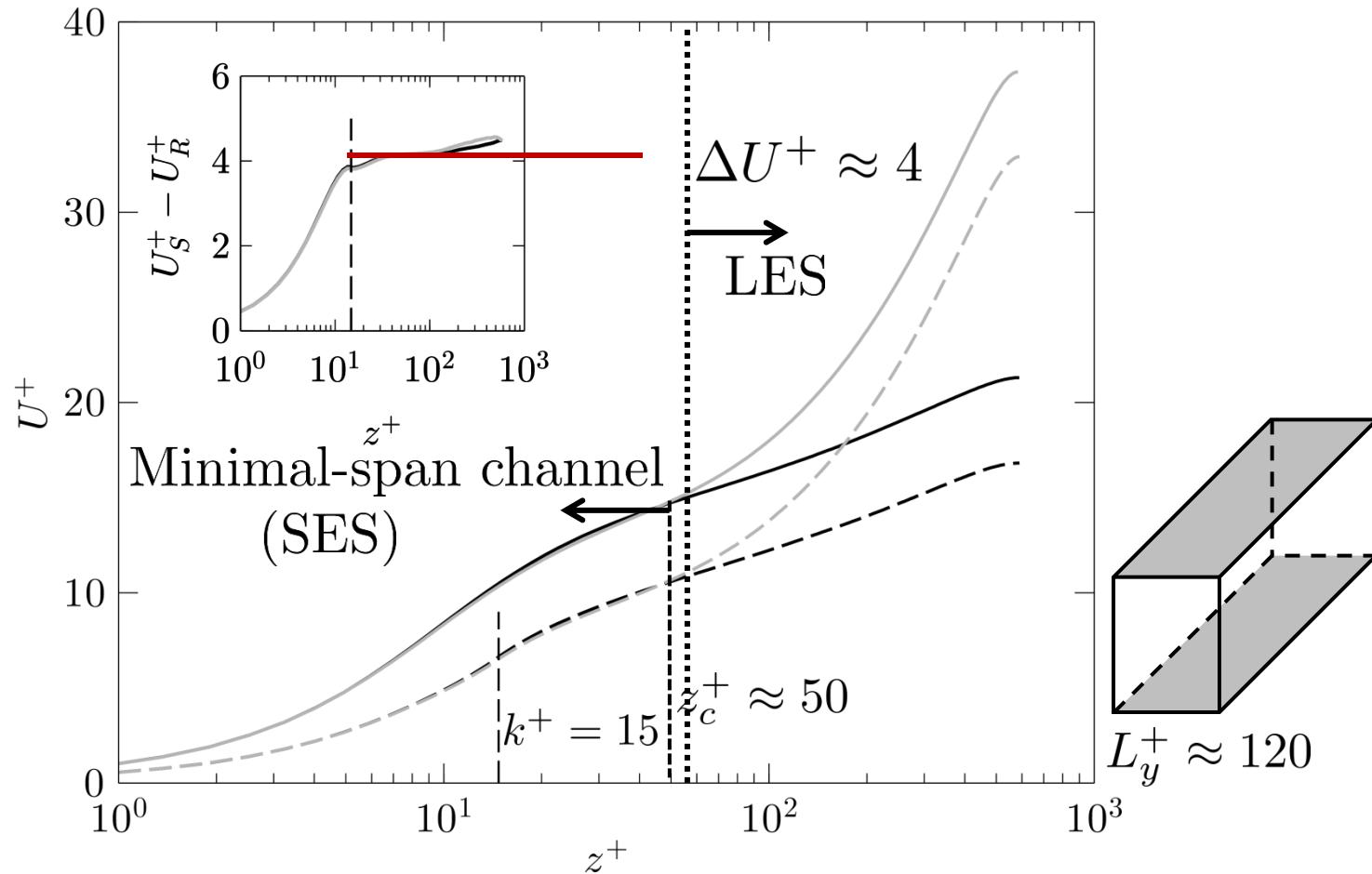
Chung *et al.* (2015, JFM), MacDonald *et al.* (2017, JFM)



$$z_c^+ \approx 0.4L_y^+$$

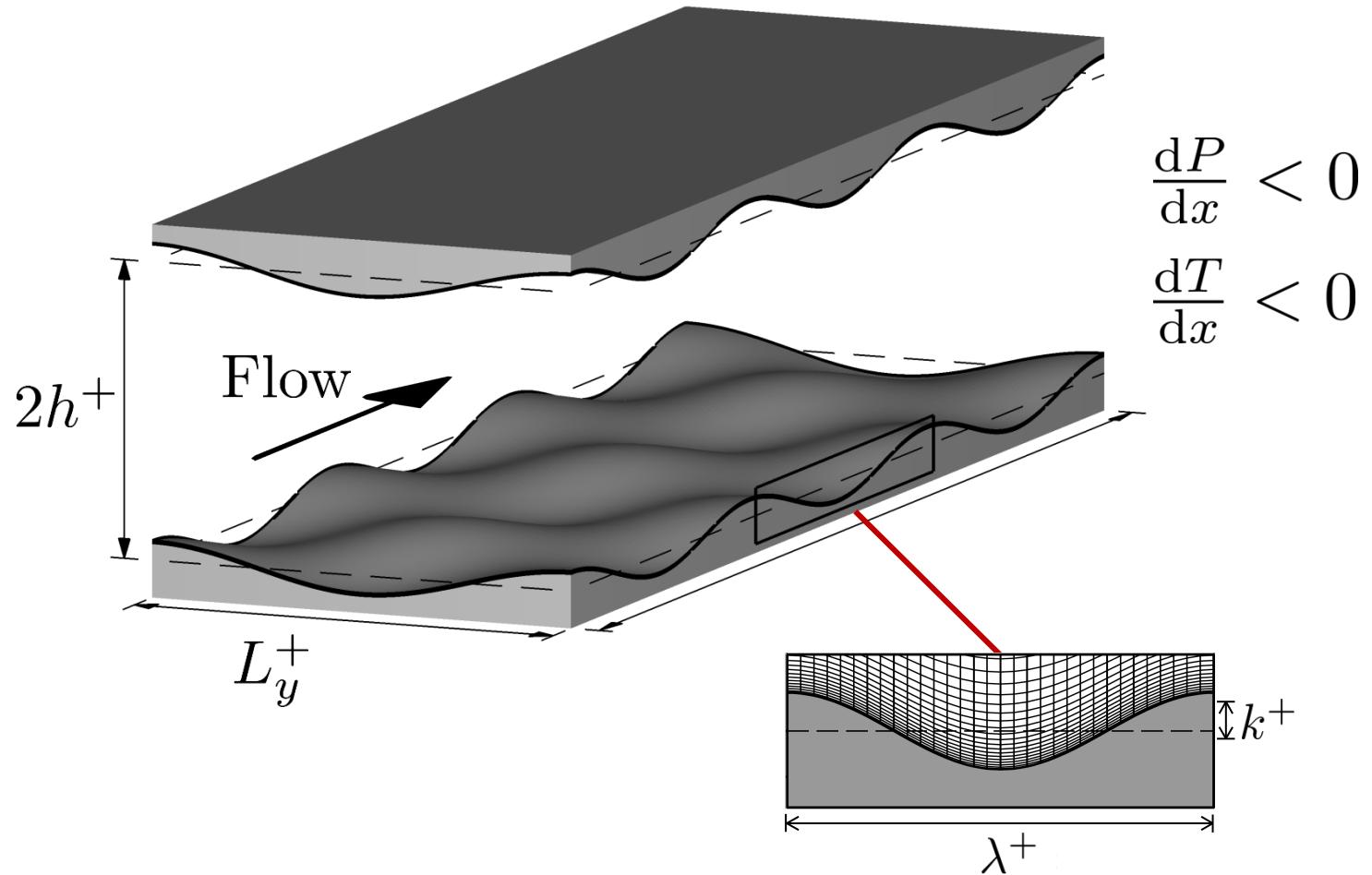
Minimal-Span Channel

Chung *et al.* (2015, JFM), MacDonald *et al.* (2017, JFM)

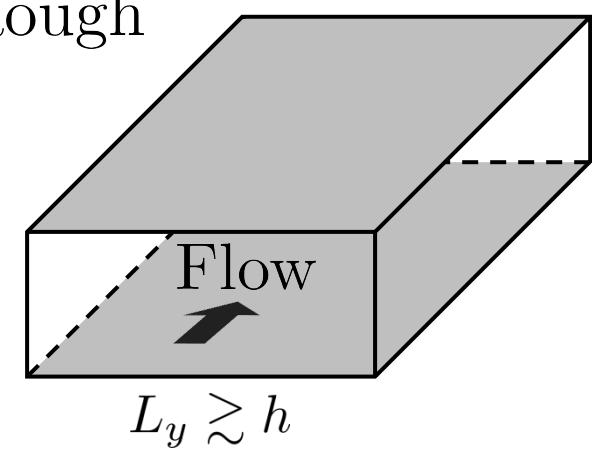
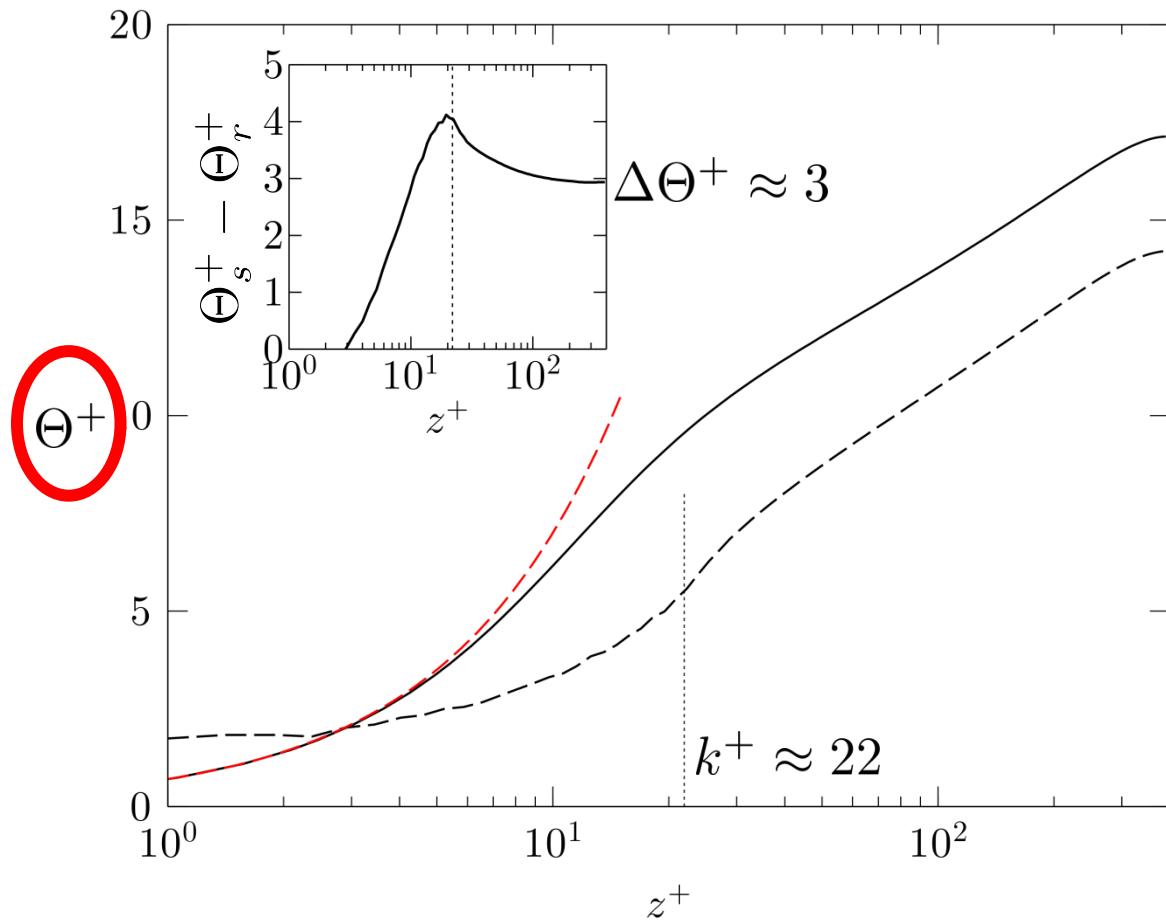


$$z_c^+ \approx 0.4L_y^+$$

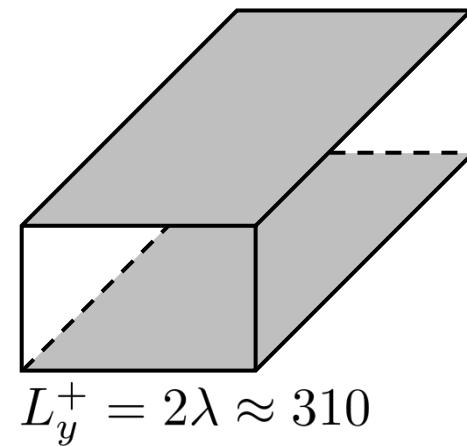
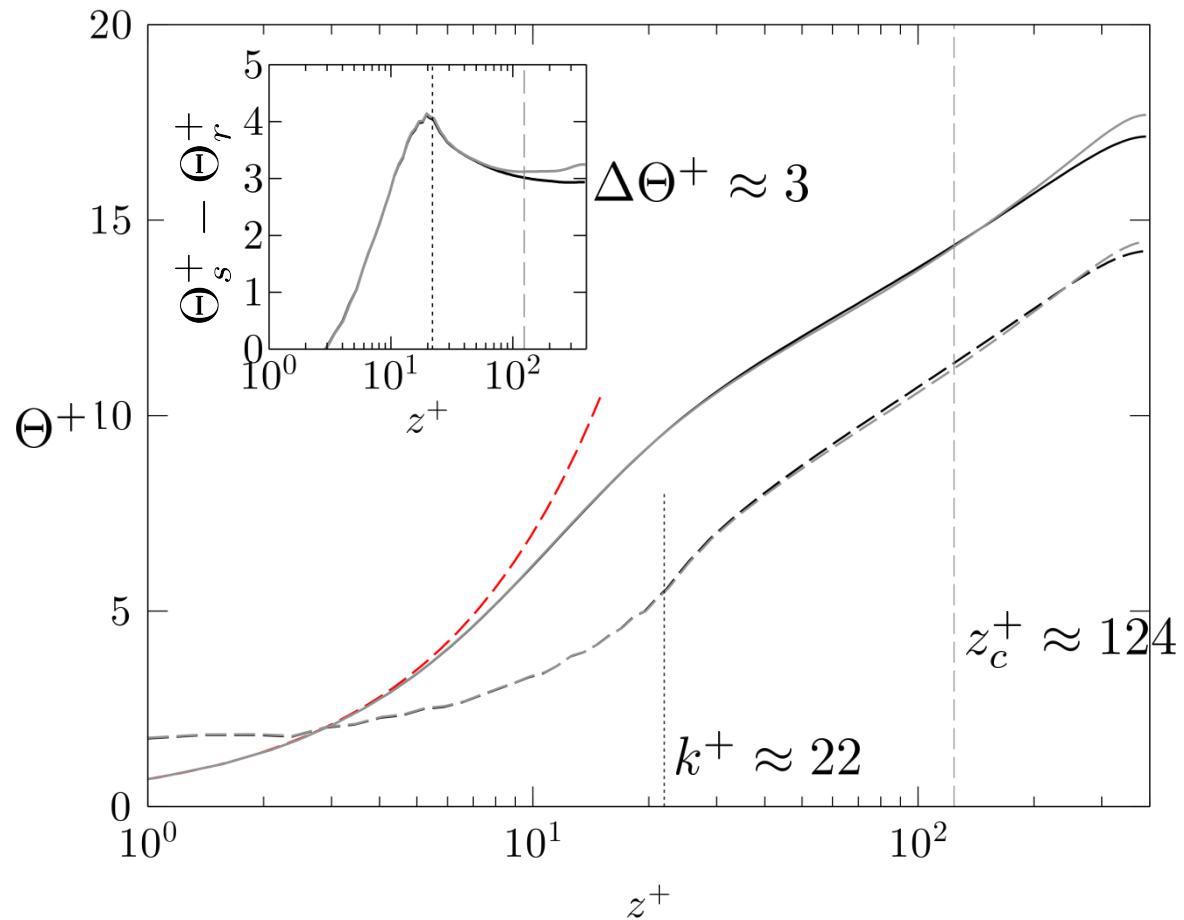
Heat Transfer



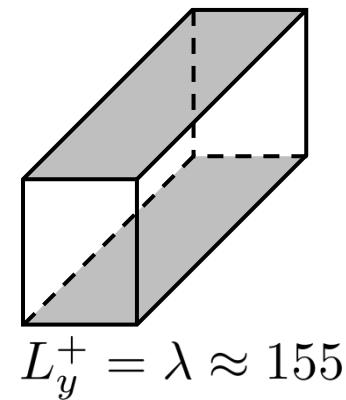
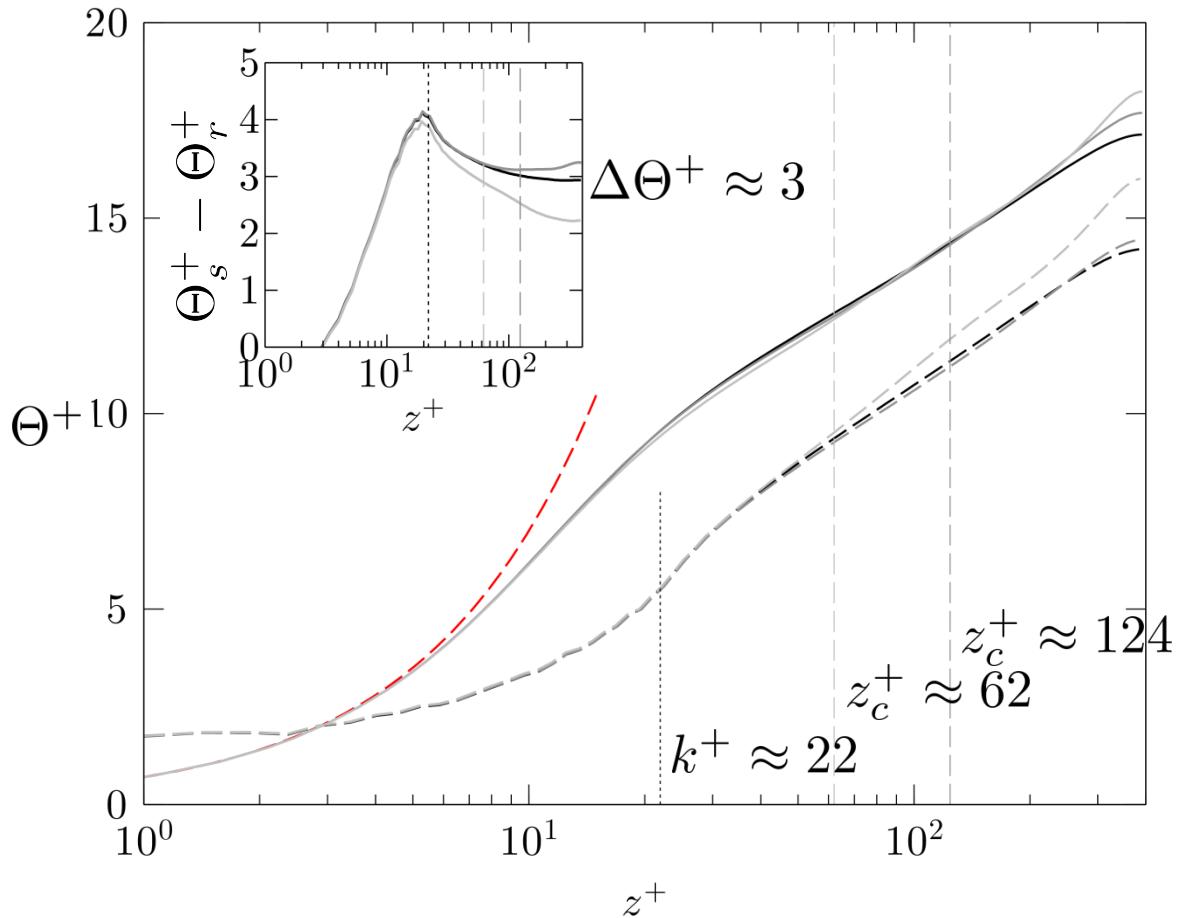
Heat Transfer



Heat Transfer

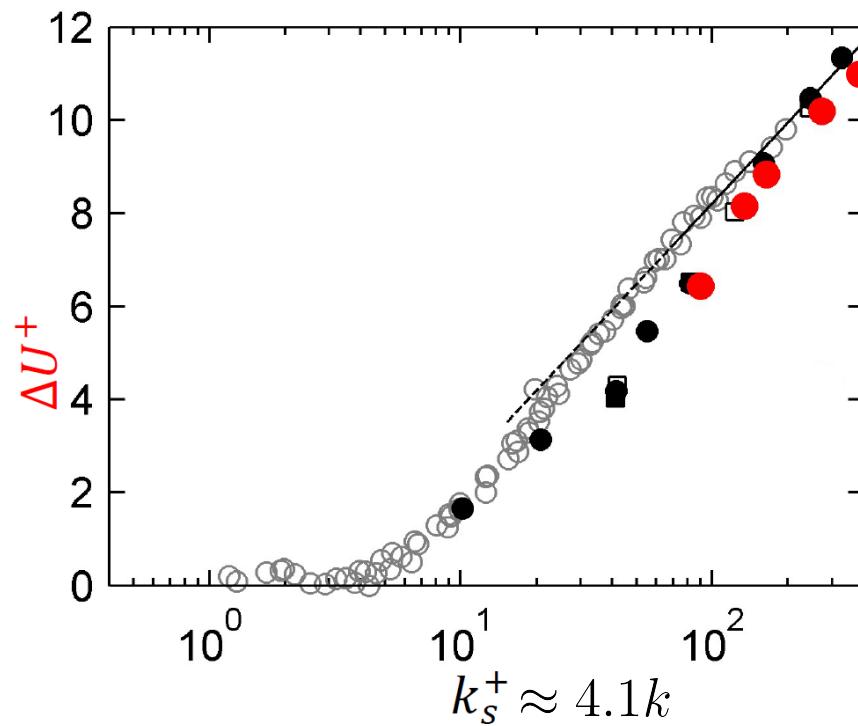


Heat Transfer



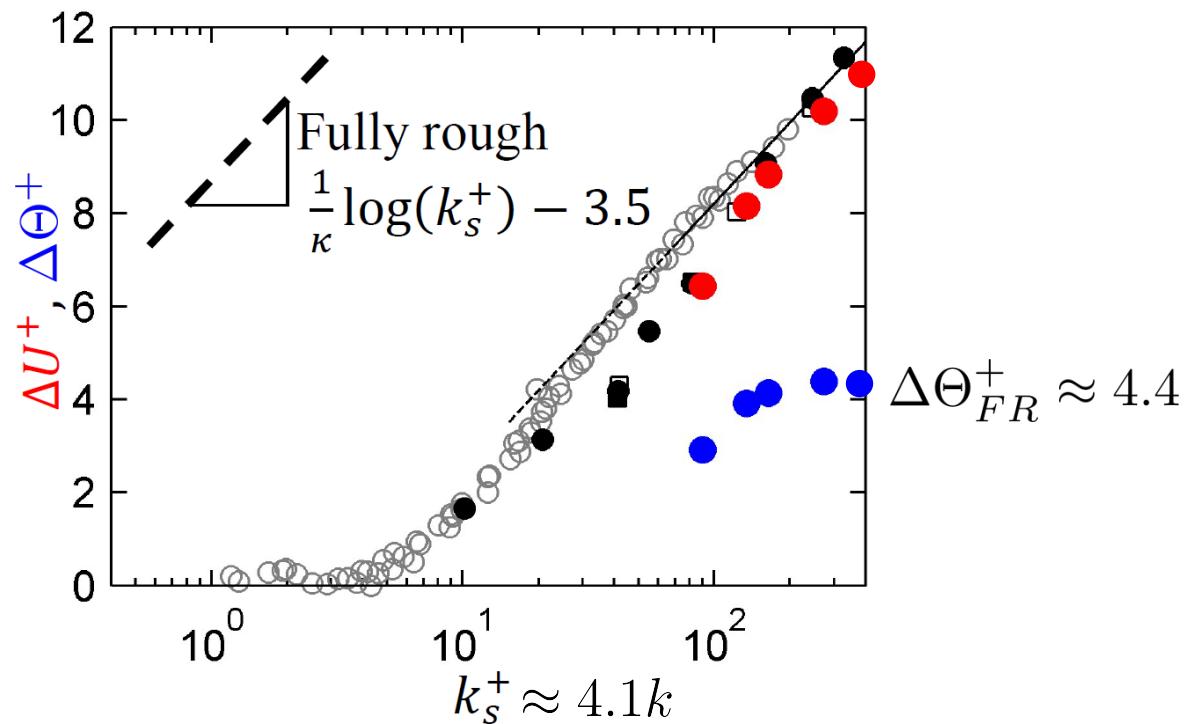
Heat Transfer - Bulk quantities

$$\Delta U^+ = \sqrt{\frac{2}{C_{fs}}} - \sqrt{\frac{2}{C_{fr}}}$$



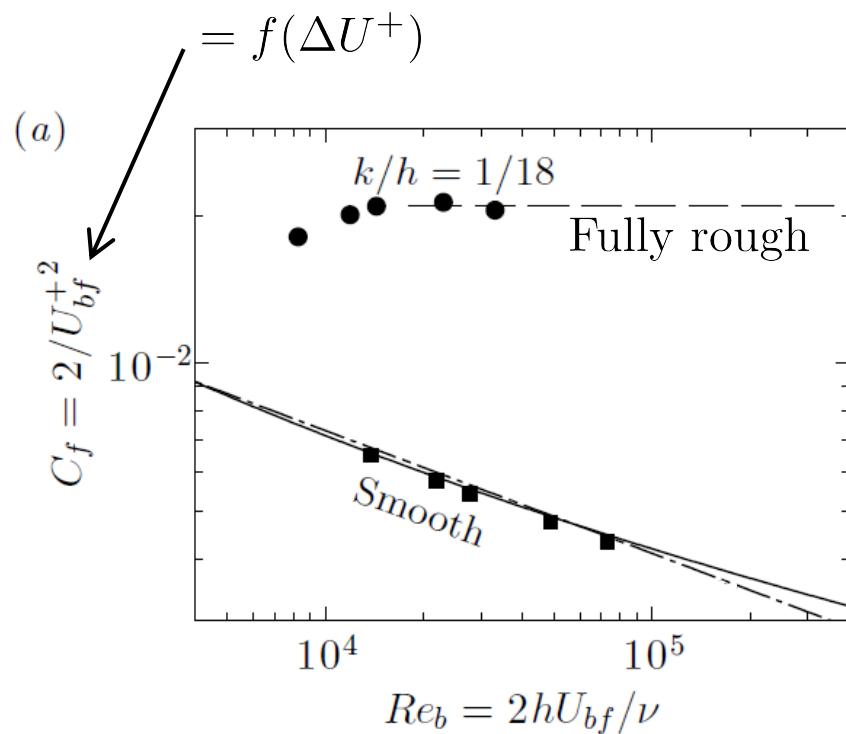
Heat Transfer - Bulk quantities

$$\Delta U^+ = \sqrt{\frac{2}{C_{fs}}} - \sqrt{\frac{2}{C_{fr}}}$$

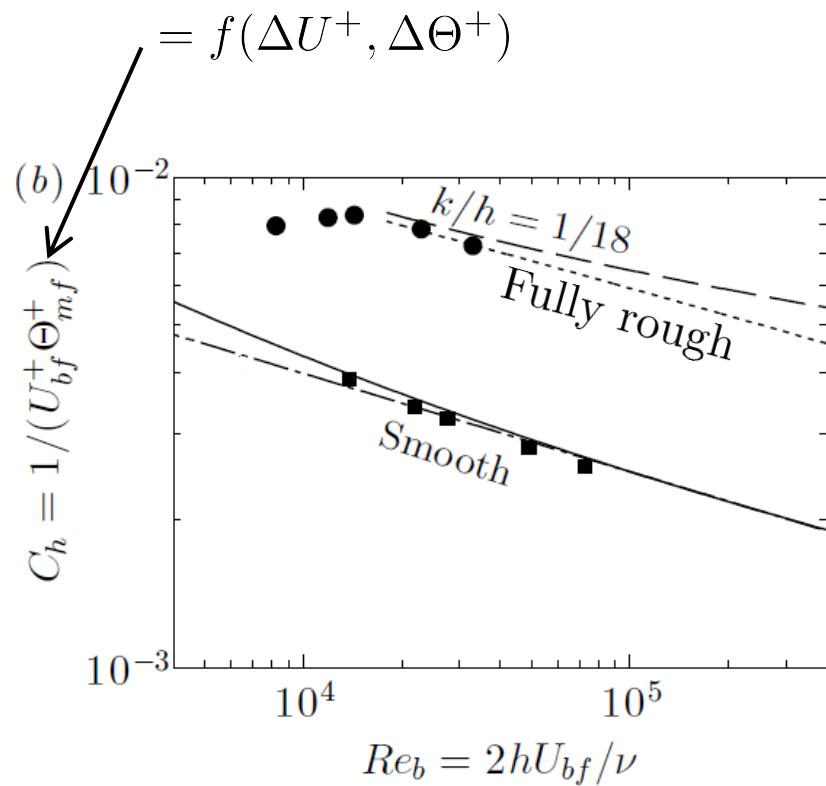
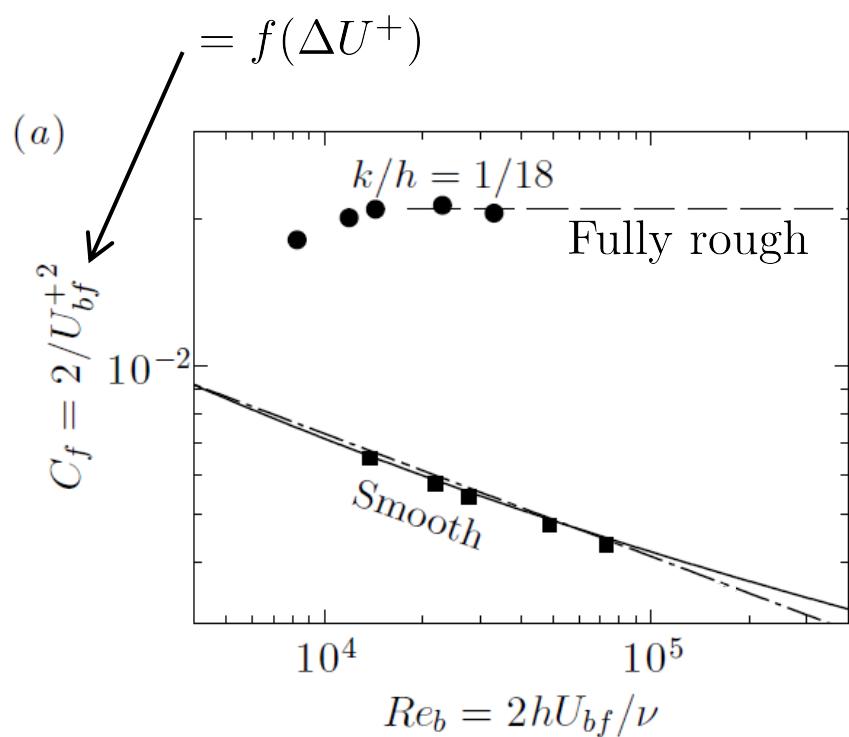


$$\Delta \Theta^+ = \sqrt{\frac{C_{fs}}{2}} \left(\frac{1}{C_{hs}} - \frac{1}{\kappa_m \kappa_h} \right) - \sqrt{\frac{C_{fr}}{2}} \left(\frac{1}{C_{hr}} - \frac{1}{\kappa_m \kappa_h} \right)$$

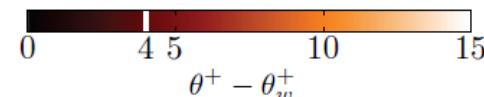
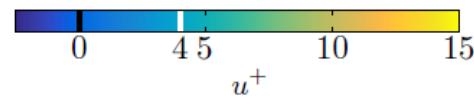
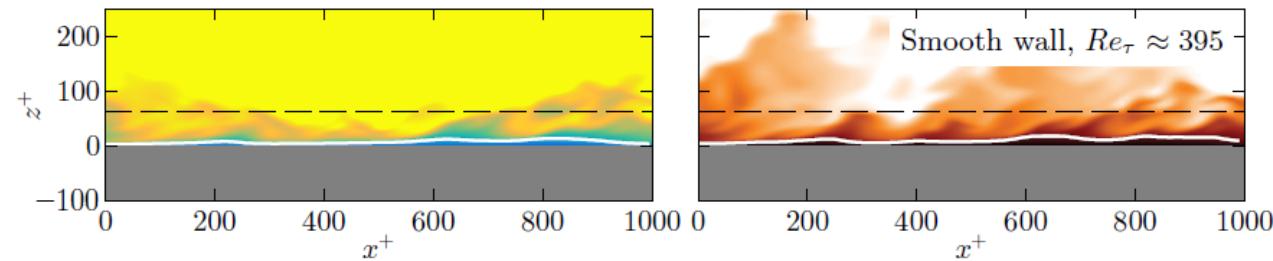
Heat Transfer - Bulk quantities



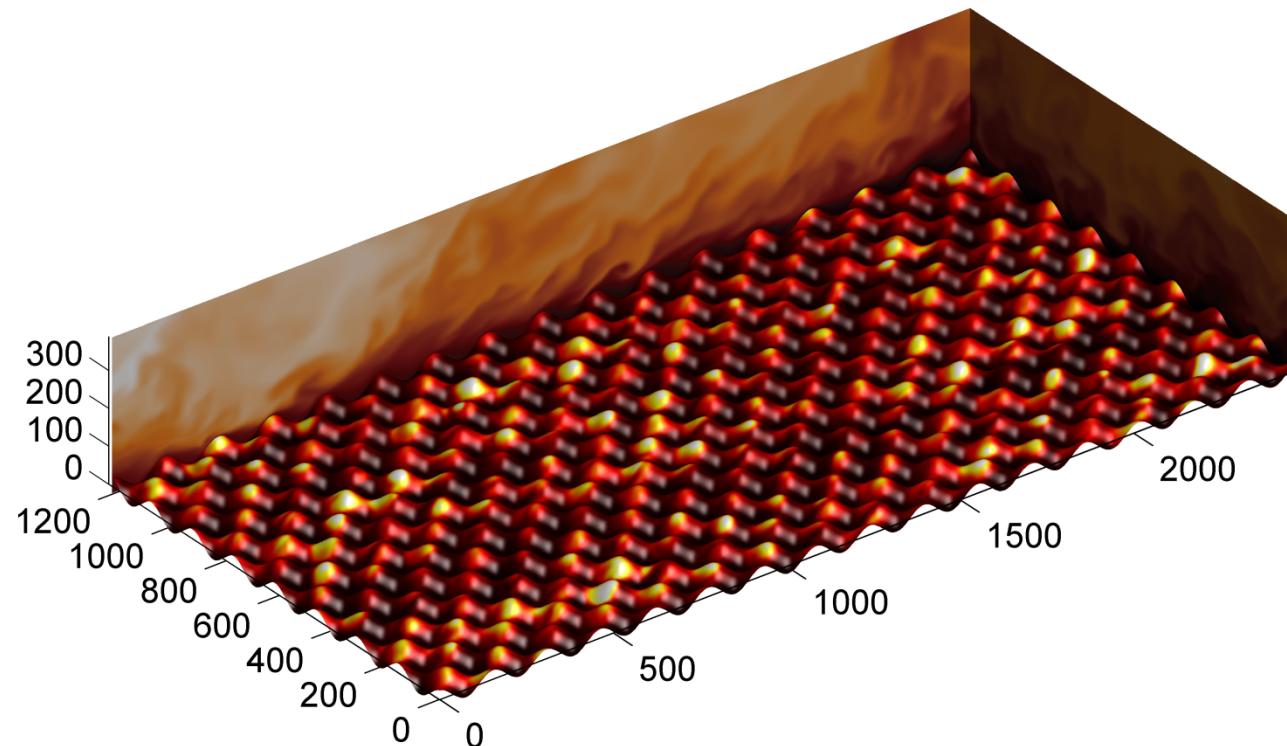
Heat Transfer - Bulk quantities



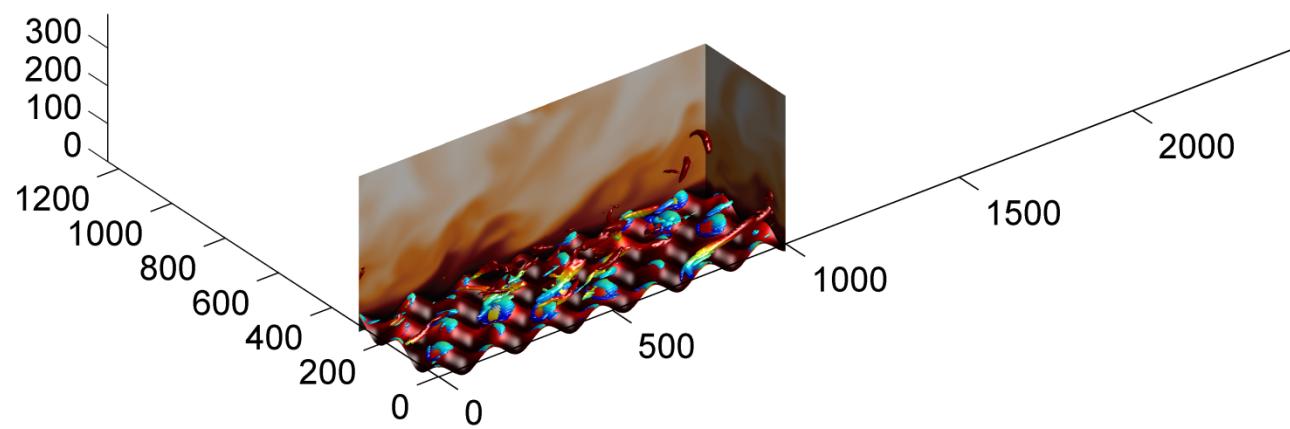
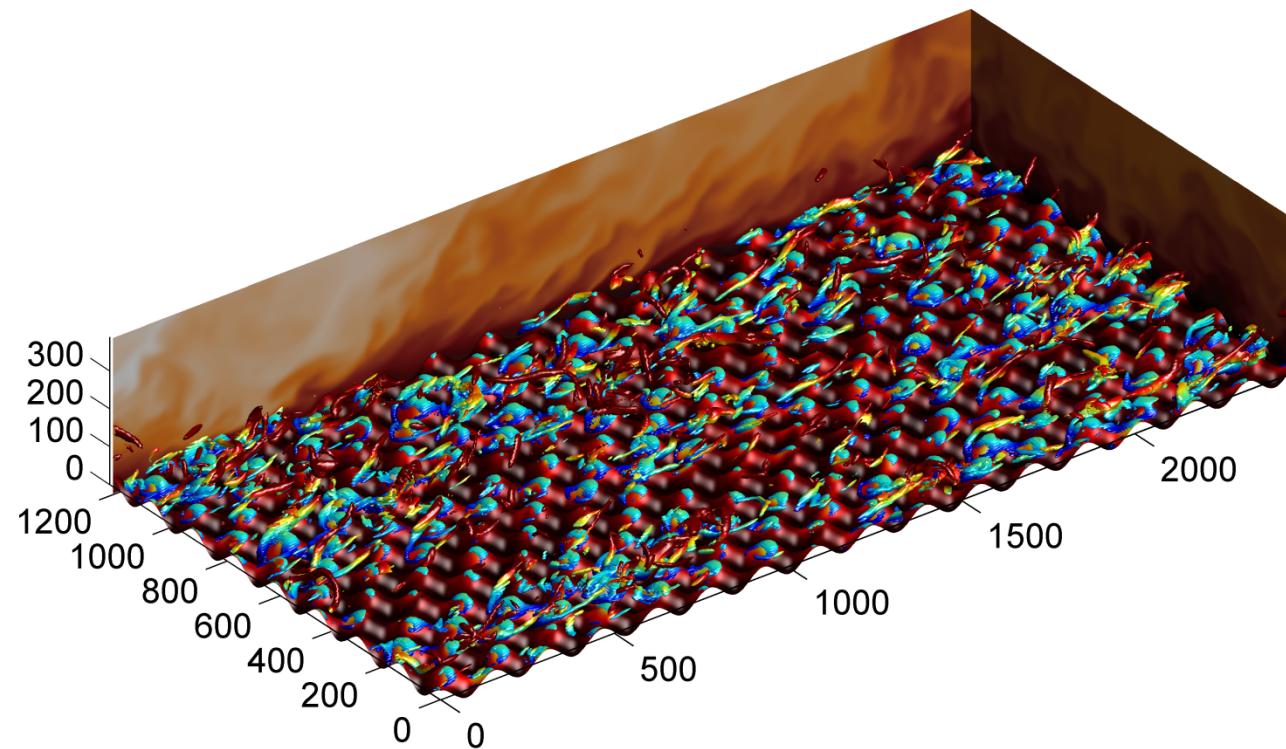
Heat Transfer



Heat Transfer



Heat Transfer



Conclusions

Rough-wall minimal-span channel

Accurately and efficiently computes ΔU^+ (or k_s)

Can also be used in forced convection to obtain $\Delta\Theta^+$

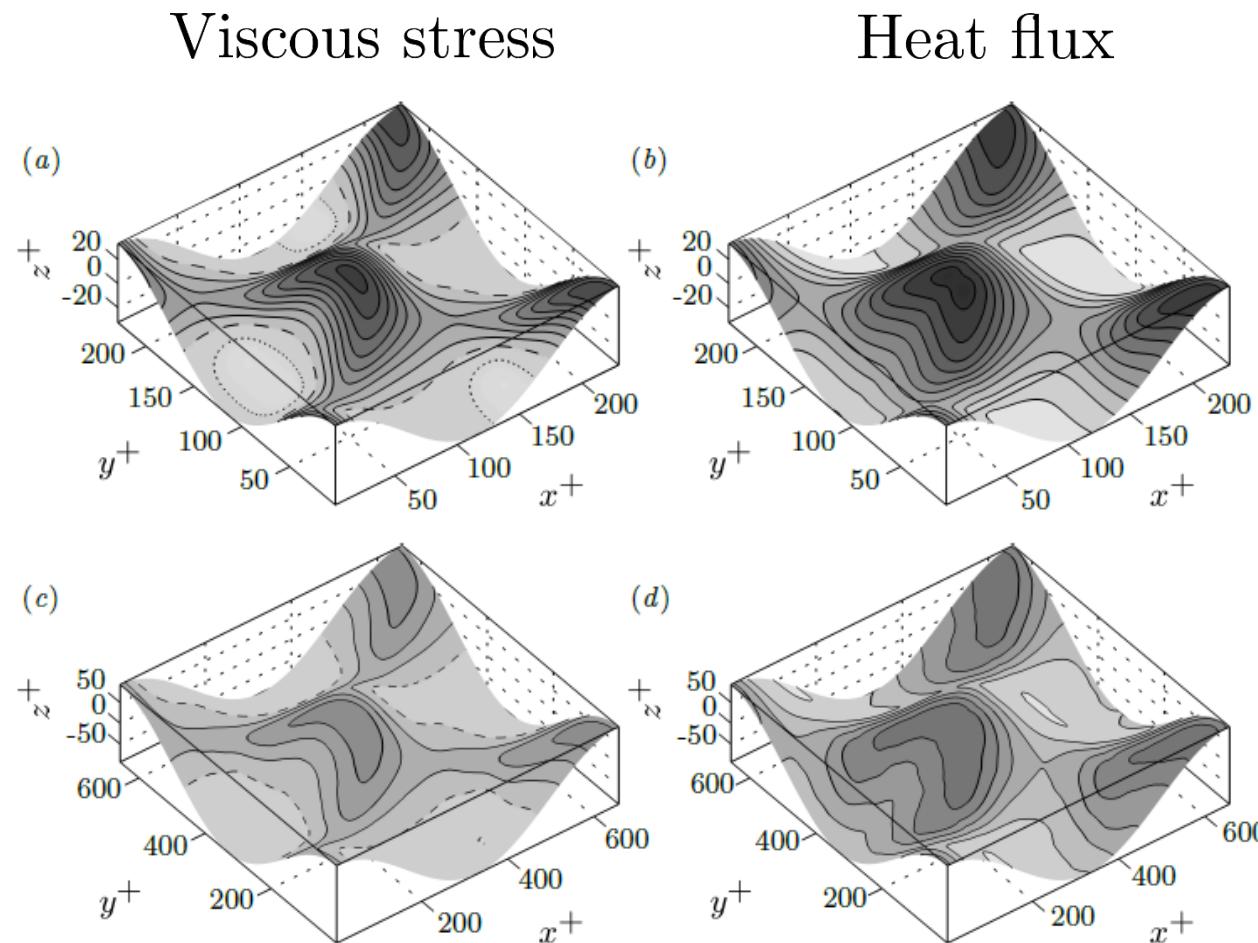
Tool to study near-wall rough-wall physics

References:

- MACDONALD, M., HUTCHINS, N. & CHUNG, D. 2018 Roughness effects in turbulent forced convection. *J. Fluid Mech.* In press.
- MACDONALD, M., CHUNG, D., HUTCHINS, N., CHAN, L., OOI, A. & GARCÍA-MAYORAL, R. 2017 The minimal-span channel for rough-wall turbulent flows. *J. Fluid Mech.* **816**, 5–42
- CHUNG, D., CHAN, L., MACDONALD, M., HUTCHINS, N. & OOI, A. 2015 A fast and direct numerical simulation method for characterising hydraulic roughness. *J. Fluid Mech.* **773**, 418–431

Appendix

Appendix



$k^+ \approx 33$
(trans. rough)

$k^+ \approx 93$
(fully rough)

FIGURE 9. (a, c) Viscous stress and (b, d) wall heat flux for roughness with (a, b) $k^+ \approx 33$ (transitionally rough) and (c, d) $k^+ \approx 93$ (fully rough). Averaged over time and for each repeating roughness element. Dashed contour shows zero stress (recirculation) region, dotted contour in (a) shows negative stress with value $-0.2U_\tau^2$. Contours are equally spaced with intervals of (a, c) $0.2U_\tau^2$ and (b, d) $0.2\Theta_\tau U_\tau$. Flow is from lower left to upper right.

Appendix

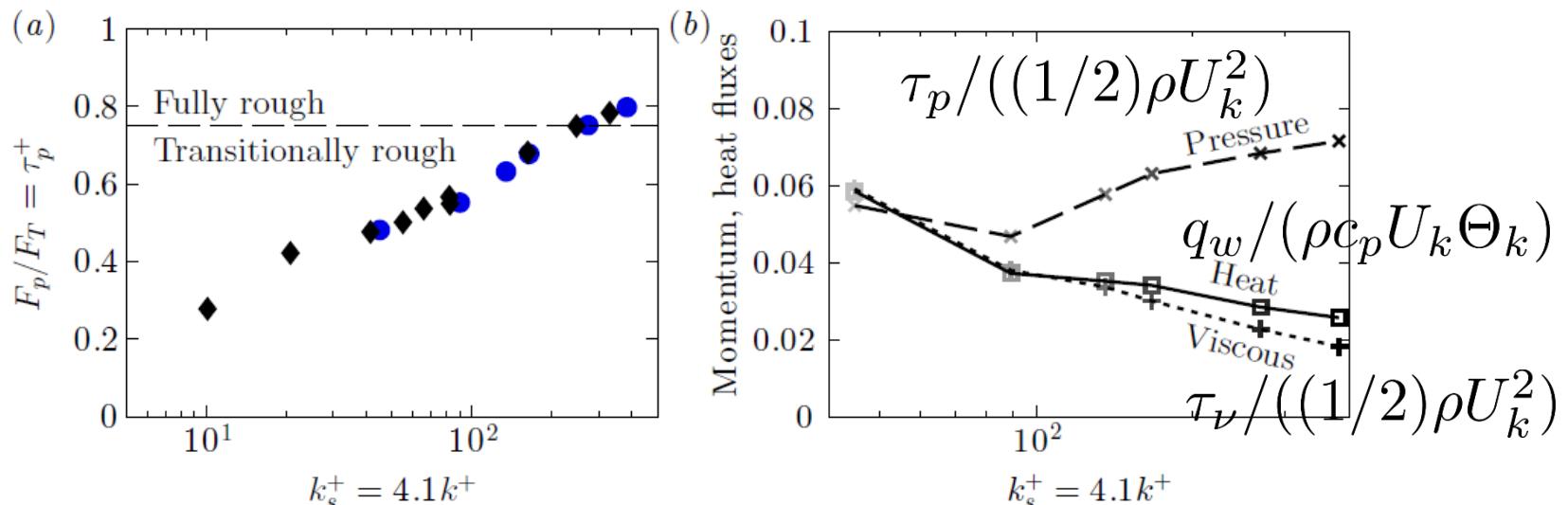


FIGURE 8. (Colour online) (a) Ratio of pressure to total drag force, F_p/F_T , against equivalent sand-grain roughness, $k_s^+ = 4.1k^+$. Symbols: ●, present data; ♦, pipe flow with the same sinusoidal roughness geometry (Chan *et al.* 2015). (b) Momentum and heat fluxes non-dimensionalised on crest velocity and temperature, U_k and Θ_k . Line styles: ——, pressure drag contribution $\tau_p/((1/2)\rho U_k^2)$; -·-, viscous drag contribution $\tau_\nu/((1/2)\rho U_k^2)$; —, wall heat flux $q_w/(\rho c_p U_k \Theta_k)$.

Appendix

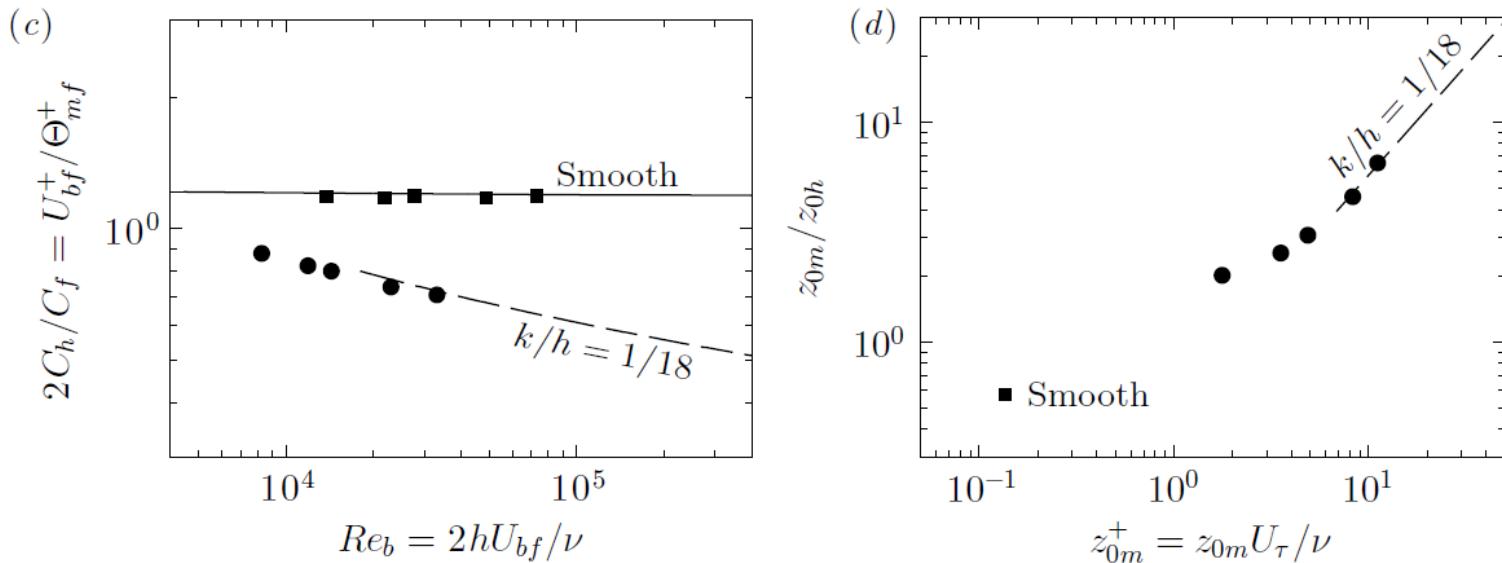


FIGURE 7. (a) Skin-friction coefficient C_f , (b) heat-transfer coefficient (Stanton number) C_h and (c) ratio $2C_h/C_f$, as a function of bulk Reynolds number $Re_b = 2U_{bf}h/\nu$. (d) Ratio of momentum and heat transfer roughness lengths z_{0m}/z_{0h} against z_{0m}^+ . Symbols: ■, smooth-wall data; ●, rough-wall data. These are estimated by fitting full-span composite profiles to the minimal channel velocity and temperature profiles for $z > z_c$. Line styles: ——, smooth-wall power-law correlations (Dean 1978; Kays *et al.* 2005); —, smooth-wall log-law estimate using (4.3) and (4.4); -·-, fully rough heat transfer model (4.5) of Dipprey & Sabersky (1963); ——, fully rough log-law estimate (4.6–4.10).

$$z_{0m}/k = \text{const}$$

$$z_{0h}^+ = \exp[-\kappa_h(A_h - \Delta\Theta_{FR}^+)]$$

Appendix

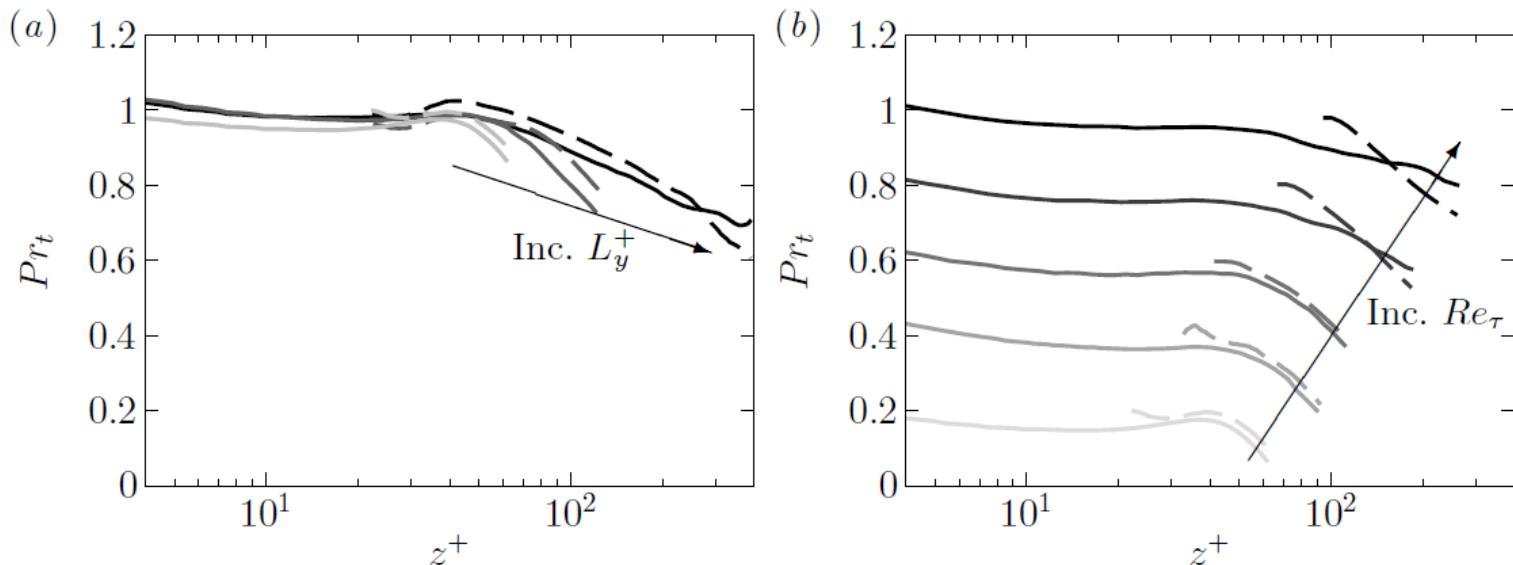


FIGURE 6. Turbulent Prandtl number against wall-normal distance, z^+ , for (a) increasing channel width with $Re_\tau = 395$ (set A, table 1) and (b) increasing Reynolds number (set C, table 1), for smooth-wall (solid) and rough-wall (dashed) flows. Data are only shown from crest to critical height, z_c^+ , and in (b) are staggered by -0.2 for decreasing Re_τ .

$$Pr_t = \frac{\nu_t}{\alpha_t} = \frac{\langle \overline{u'w'} \rangle}{\langle \overline{w'\theta'} \rangle} \frac{d\Theta/dz}{dU/dz}$$

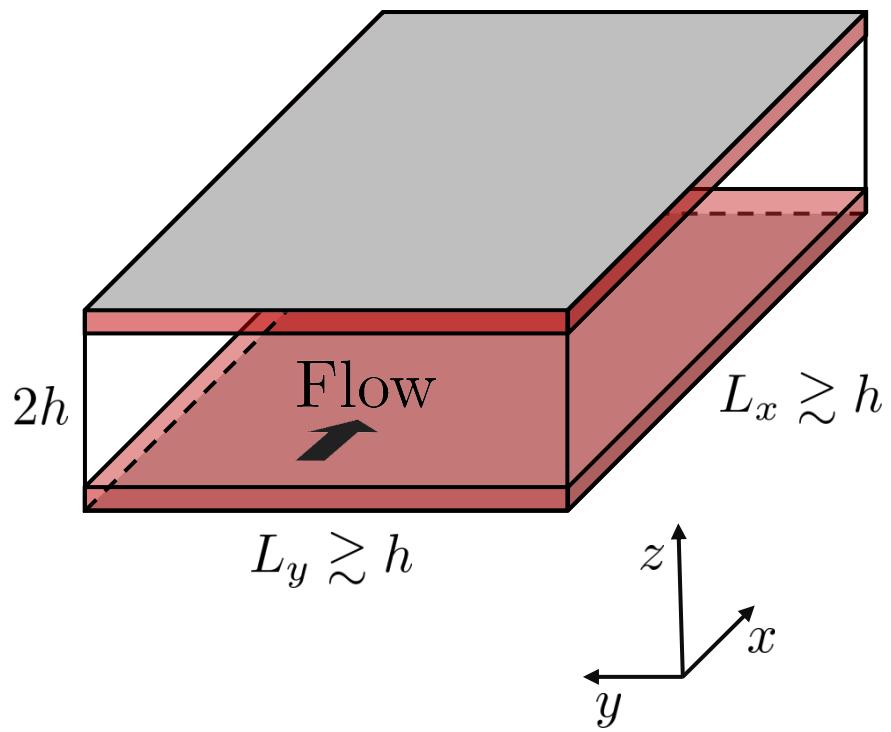
Minimal-Span Channel

$Re_\tau = 590$

$N_{cells} \approx 181$ million

CPU hours $\approx 281,000$

\$11,200



$N_{cells} \approx 3$ million

CPU hours $\approx 16,400$

\$660

